THE SAHARAN - ORDOVICIAN ICE AGE:
EVIDENCE FOR A GLACIATED CONTINENT

by

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INTRODUCTION

The existance of the Ordovician Ice Age has been confirmed only within the past fifteen years or so, a relatively recent finding when compared to vast amount of compiled works on other ice ages. The inital discoveries were made by French petroleum geologists in the 1960's during reconnaissance surveys of the central Sahara Desert. With subsequent evidence uncovered from Saudi Arabia extending 6000 kilometers westward to Sierra Leone, the Ordovician glaciations are now recognized as being one of the most extensive continental scale glacial episodes to have affected the Earth. The exceptional preservation of deposits makes this realization all the more convincing.

The scope of this paper is twofold. A discussion of some of the more popular reasons thought to be responsible for major ice ages is synthesized, though it is evident that this puzzle is far from complete. Nonetheless, a recounting of possible trigger mechanisms involved in glaciation periods are important to any discussion on major ice ages and should contribute to the understanding of events occurring on the northern half of the African craton during the Saharan-Ordovician glaciations.

THE PROBABLE CAUSES OF MAJOR ICE AGES

Probably the most controversial question affecting the study of past ice ages is that of cause. What are the factors, operating either separately or in conjunction with one another, which are responsible for the iniation of significant cooling necessary for glaciation? Glaciation represents a particular hydrological response to atmospheric conditions which allow for the accumulation of snow to exceed ablation. To be sure, several basic assumptions come to mind. The necessity of a moisture supply in a cold climate is fundamental to assure continued growth of large scale ice sheets. What, however, can be said about the trigger mechanism(s) which result in the initial onset of glaciation?

To begin with, on the present day earth, there is a rather consistant zoning of climatic regions into more or less fixed latitudinal belts. These are governed by basic circulation cells involving both the upper and lower atmosphere, which, in conjunction with oceanic currents, are the prime mechanisms for energy transfer between the equator and the poles (Oliver, 1984). These are subject to seasonal change, but over the vast course of geologic time, the climatic zones are postulated to have remained relatively constant.

Alfred Wegener, the founding architect of the continental drift theory, used this as a prime argument in advancing the continental drift theory. Being a meteorologist, he realized that on a round earth heated by a single source, it is geologically more realistic to move continents, by whatever means necessary, than it is to shift climatic zones (Beaty, 1978).

In order for the iniation of a continental-scale ice age to occur, two basic requirements must be met. First, for ice sheets to grow and survive in areas previously unaffected by glaciation, a global lowering of temperatures must occur such that snowfall becomes one of the main forms of precipitation. The temperature must remain cold so that the snow can change into firn and remain as such during the summer months rather than melting away. In addition, there must be an adequate moisture supply available to the area which will provide the raw meterial out of which the glacier is composed (John, 1979).

Obviously, if the assumption of constant climatic zoning is correct, then the positioning of continents in the high latitudes by continental drift would at least allow for a lowering of temperatures on those respective continents. Hence paleomagnetic data used in correlating the past locations of the earth's magnetic poles becomes indispensable since it will provide a record of what land areas were in a situation where temperatures were cold enough for glaciers to exist. Given this requirement, the extent of glaciation can then be increased by climatic feedback mechanisms within the high latitude areas which will tend to cause further build-up and extend the region affected by glaciation into the mid-latitudes (John, 1979).

There are several factors which must be considered if one accepts continental drift as the prime mechanism responsible for glaciation iniation. The first is that a location termed as "polar", is not always the most favorable location for ice sheet build-up. It is true that polar regions are certainly cold, yet there is a tendency for them to be quite arid also. There are vast areas within the polar regions today, namely Alaska, North Greenland, and Siberia which are quite unsuitable for glacier development. In addition, there is a tendency for the poles themselves to shift throughout time, somewhat analgous to the wobbling motion of a top as its spin rate decreases. This mechanism could act independently of continental drift in altering favorable locations for glacier development (John, 1979).

The importance of continental drift certainly can not be downplayed. The climatic potential naturally exists, and always has existed at the poles as opposed to areas located further into the mid-latitudes. It is the proper positioning of continents, both in proximity to the poles and with respect to an adequate moisture supply, which is the fundamental requirement for the occurrence of major ice ages. There are, however, many other factors which should be considered; possibly not so much as fundamental requirements, but rather in terms of trigger mechanisms to be considered in conjunction with continental drift.

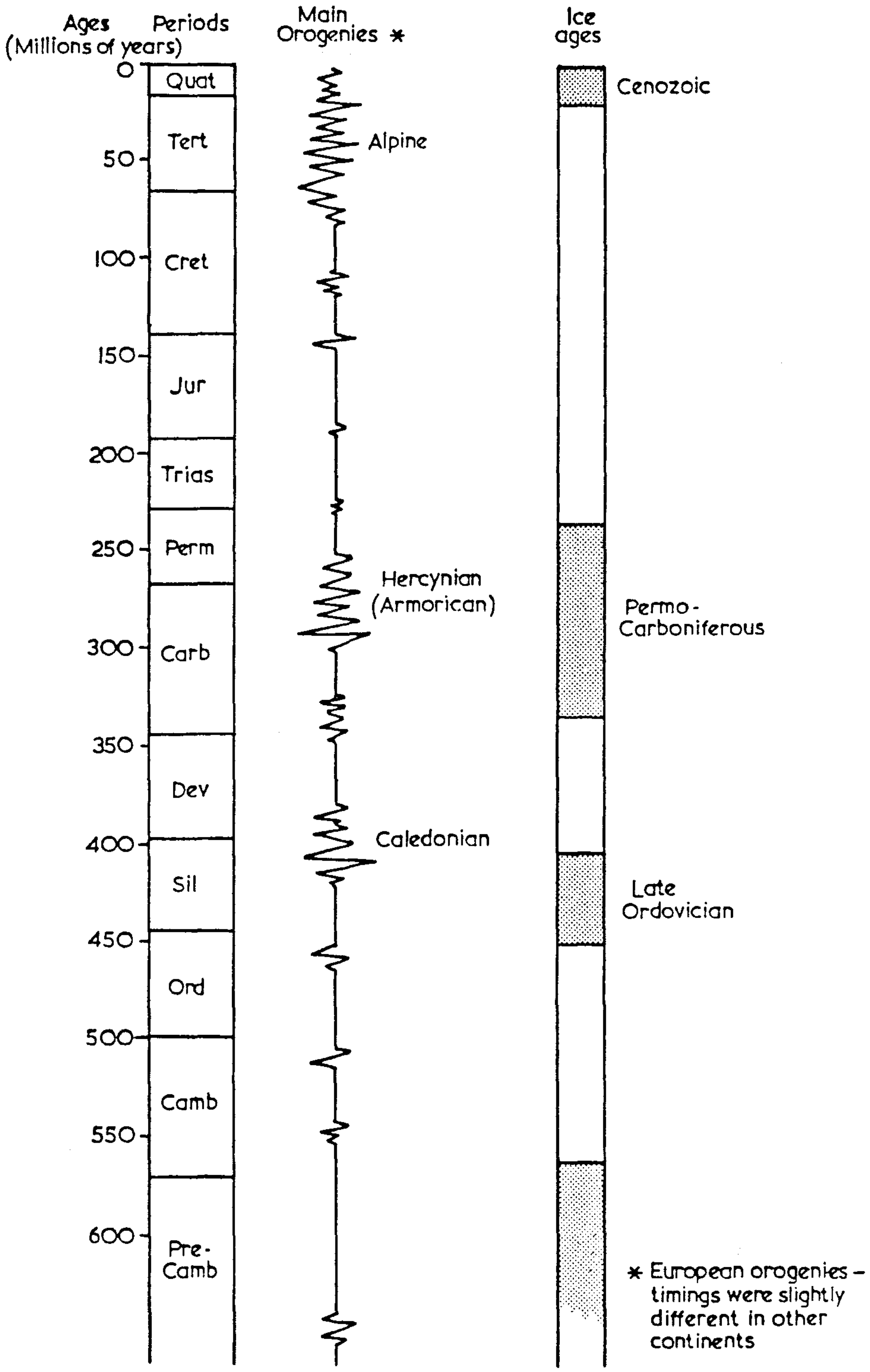
Contributing Factors

Although the high latitudes, particularly Antarctica and Greenland, are the locations for the only continental-scale ice sheets today, it is quite evident that they are not the only sites for modern glaciation. Alpine glaciation is an important process affecting many of the world's higher mountain ranges. When the land surface is elevated such that there is a substantial increase in surface area above the snowline, the conditions will favor increased accumulation and valley glacier development. The centers of alpine glaciation originate from the mountatins in the form of cirque glaciers and snowfields. These will then extend down into the surrounding valleys, provided a moisture is located nearby. This is best exemplified if a mountain range is located on the western edge of a continent, within close proximity to an ocean and aided by a regular westerly wind flow. As long as the mountains remain at high altitudes and at relatively the same latitude, this effect will be continued (John, 1979).

The question of whether or not orogeny is a significant factor in the development of large scale continental glaciation, is a much debated one. High mountains have probably always existed somewhere on the earth's surface at one location or another and that during periods of extended continental glaciation, subtropical and even tropical locations have supported limited alpine glaciation. However, oweing to the rarety in dimensions of large scale continental glaciation, the relationship between this and orogeny has probably been a coincidental one (Beaty, 1978).

The evidence neither proves nor disproves a cause and effect relationship. Figure 1 shows a graphic representation of the major orogenys throughout the Phanerozoic and the occurrence time frames of major ice ages. The major Alpine Orogenies of the Tertiary preceded the Pleistocene glaciations while the Caledonian Orogeny postdated the Late Ordovician glaciations. The Permo--Carboniferous glaciations, thought to be the maximum extent in world-wide glaciation both temporally and spatially, coincide with the Hercynian Orogeny. Care should be exercized in demonstrating an exact cause and effect relationship, although orogeny certainly can be considered to play a supplementary role, at least in adding increased ice volume.

There are several additional factors which are thought to play supplementary roles or serve as possible trigger mechanisms for continental glaciations. Changes in oceanic circulation



The spacing of periods of mountain-building and ice ages during the last 600 million years. The main orogenies occurred at different times on the various landmasses, although a number of particularly pronounced and widespread mountain-building episodes can be discerned on all of the continents.

(Figure 1; John, 1979)

patterns have also been suspected in playing some role at least in terms of short term atmospheric variation and associated cooling. Lamb demonstrated that atmospheric temperatures, pressure distributions, and general circulation patterns clearly respond to changes in sea-surface temperatures. Continuation of such changes would arguably have some effect on overall temperature and precipitation (Beaty, 1978; after Lamb, 1972). However, action/reaction effects between the ocean and the atmosphere are intertwined at so many points that they can not be inferred except over the short term time period which they are considered. Indeed, over longer periods of time, it is generally assumed that the atmosphere has led and the oceans have followed (Beaty, 1978).

Most meteorologists will agree that heat transfer at the surface, dictated primarily by the amount of insolation (incoming solar radiation), is the primary mechanism involved in atmospheric circulations, and is thus directly responsible for the zoning of latitudinal climatic belts. It has been postulated that changes in solar radiation might be expected to produce variations, including swings towards conditions which would favor the onset of glaciations. Short term cooling effects, such as those noted during the Little Ice Age of the 17th through the early part of 20th century, have been correlated in part to a decrease in sunspot and solar flare activity. In addition, the solar constant, a flux value of insolation received at the top of the earth's atmosphere has been studied extensively and has been shown to vary by amounts on the order of 20 to 40 Watts per square meter during the past century.*

* the value of the solar constant is at present estimated to be approximately 1353±20 Wm^{-2} per day. At the beginning of the 20th century, it was estimated to be 1393 Wm^{-2}.

Again, a clear-cut cause and effect relationship has yet to be established (Beaty, 1978). Instead, over the long term geologic time scale, the basic argument put forth in the consistancy of climatic zones has been that the amount of solar radiation received has remained more or less constant (John, 1979).

Basic changes in the components of the earth's atmosphere have also been a suspect in leading to climatic change. For example, a large increase in water vapor content would affect the climate through an increase in the thickness and extent of the cloud layer, leading in turn to a reduction in the amount of solar radiation reaching the earth's surface. Conversly, a slight increase in water vapor would probably lead to a warming of temperatures due to a corresponding increase in the heat retaining capacity of the atmosphere (John, 1979). The discussion over the role of atmospheric CO_2 content has long been argued. The so-called "greenhouse effect" deals with the role CO_2 plays in the balance between incoming shortwave solar radiation and outgoing longwave terrestrial radiation. As long as sufficient CO_2 exists in the atmosphere, the amount of heat retained will also be proportional. The planet Venus is an extreme example whose thick and cloud--shrouded atmosphere causes the surface to glow red due to the extreme greenhouse effect there. It is thought then, that a decrease in atmospheric CO_2 content would lead to a corresponding decrease in the amount of longwave radiation trapped, hence an overall decrease in global temperatures. The inconsistancies of agreement, however, in how much cooling would occur has long been debated. Halving the amount of CO_2 concentration in the atmosphere has produced theories ranging from only a 3°C lowering of global temperatures to completely iceing over the entire globe (John,1979). In addition, cause and effect relationships are difficult to establish due to the complexity of the carbon cycle; involving plants, animals, volcanic gasses, chemical weathering, carbonate fixation in rocks, oceanic carbon concentrations, and recently, the increased burning of fossil fuels (Oliver, 1984).

Particulate matter suspended in the atmosphere has long been known to affect atmospheric temperature. Short term effects in the lowering of temperatures are well known and are basically due to the scattering and absorption of the direct solar beam. It is expected then, that large amounts of volcanic dust will result in an overall cooling of the atmosphere and that continued persistance of such an effect would in turn affect some phases of the hydrological cycle; possibly influencing the iniation and continuation of glaciation. Problems arise again, in long term correlations. Random volcanic activity has existed throughout geologic time and periods of high volcanic activity as recorded in the rock record, have but infrequently coincided with major episodes of glaciation. It is judged by many authors to be an inadequate explanation by itself for the iniation of continental glaciation although, in conjunction with other factors, may act as a critical element leading to the onset of glaciation (Beaty, 1978). Certainly, prolonged volcanic activity would have to be fundamental since the effects of isolated volcanic eruptions-- the suspension of volcanic dust in the atmosphere-- have been demonstrated to dissipate usually within five to seven years after the initial eruption (John, 1979).

The role played by surface albedo, or surface reflectivity, has been studied by climatologists for years. It is well known that the location of snow and pack ice fields constitute one of the most important seasonable variables in the earth's heat balance. Surface albedo at the poles is the prime reason for the loss of heat in these regions since the sun's rays strike highly reflective snow and ice fields at an increasingly oblique angle the higher in latitude one progresses. Atmospheric modeling studies indicate that reducing the surface albedo by either partially or completely eliminating the polar ice caps have yielded calculated temperature changes in the equatorial and polar regions of +2°C and +17°C respectively. Clearly, albedo manipulation at either pole could have global repercussions (Beaty, 1978). However, only a sustained increase surface albedo would have a stake in long term climatic variability. In searching for possible trigger mechanisms, it seems that a sustained increase in surface albedo producing a self-accelerating feedback mechanism allowing for further increase, could provide the necessary trigger when coupled with other factors (Beaty, 1978).

A much debated possible cause of ice ages has been the astronomical periodicity variations studied by the Yugoslav geophysicist Milankovitch during the 1920's. These involve the frequencies of astronimical variables in the earth's orbit. This is basically the systematic changing in the orientation and inclination of the earth's axis coupled with longer term eccentricity variations in the earth's orbit therby leading to variations in seasonal insolation at any given latitude on a cyclic recurring basis (Beaty, 1978).

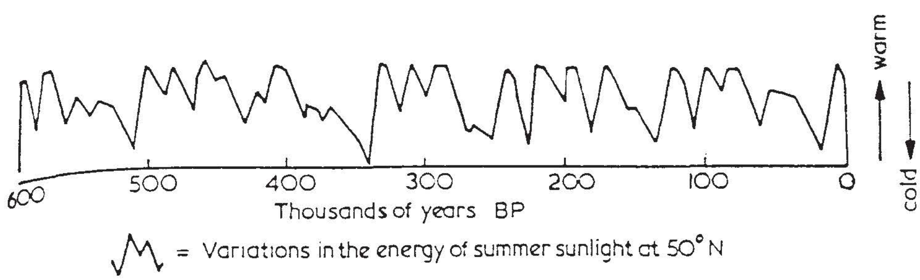
The factors involved yield the following frequencies:

1) Precession of the equinoxes: 21,000-25,000 years

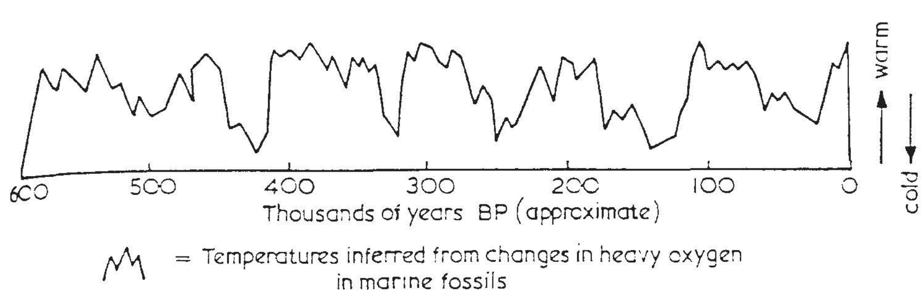
2) Obliquity of the ecliptic: 41,000 years

3) Eccentricity of the earth's orbit: 90,000-100,000 years

Referring to figure 2, there seems to be a rather decent matching between variations caused by the above variables and temperatures inferred from O^{18} ratios of marine fossils. Many scientists feel that there is a fundamental link between glacial-interglacial cycles and the Milankovitch cycles. The key problem with embracing this relationship is that there is only a partial correlation existing mainly for only the Quaternary fluctuations. Arguably, there should be more widespread glacial activity throughout the Phanerozoic if this theory is to be accepted as a primary mechanism (John, 1979). However, combined with other factors and favorable continental positions, it is very plausible.



Curve showing variations in solar radiation receipt at the Earth's surface over the past 600,000 years. This is a modified version of one of the curves calculated by Milankovich



Changes in heavy oxygen concentration in marine organisms (after Hays, Shackleton, Imbrie). Note the approximate correlation with Milankovich 'cycles'.

(Figure 2; John, 1979)

Given the abundance of theories concerning the causes of major ice ages, it would be beyond the scope of this paper to go into very much detail about anything other than the possible factors involved. More than likely, several factors in conjunction with favorable continental positioning must operate simultaneously to trigger an ice age. Often, these will be chance occurrences and it is evident that they must operate over an extended period of time in order to produce positive feedback mechanisms necessary for the prolonged growth of major ice sheets.

The Little Ice Age of the 17^{th}-20^{th} centuries provides an interesting example of a number of the previous mechanisms discussed which were operating in conjunction with one another. Decreasing sunspot activity indicative of less solar radiation outpur and frequent volcanic activity led to a significant lowering of the snowline, an increase in regional snow cover in many polar and mountainous regions, and a subsequent decrease in worldwide temperatures. With this, a general increase in the surface albedo also occurred. Why then, with the ingredients for a positive feedback mechanism at hand, did this cooling effect terminate? Apparantly the orientation of Earth-Sun geometry, variables in the Milankovitch cycles, during the past several thousand years,have yielded relatively high amounts of wintertime insolation in the Northern Hemisphere (as opposed to those values calculated for the time period of 10,000 to 18,000 years ago.) Evidently, high wintertime insolation would appear to overcome short-term cooling effects produced by the chance occurrence of other trigger mechanisms.

From this example, it is clear that the variables responsible for triggering an ice age are highly interdependant. To be sure, there have been an abundance of relatively minor ice ages similar in dimension to that of the Little Ice Age while the occurrence of major continental ice ages documented is rather rare. There are, however, some interesting tendencies noted in the regular recurrence of ice ages throughout the Phanerozoic and into the Late Precambrian. Table 1 illustrates the relative time interval which has occurred between major ice ages.

The Spacing of Ice Ages Through Geologic Time

Name of Ice Age	Approx. Age	Approx. Duration	Geologic Period
Cenozoic	1 million years	10 million years (so far)	Quaternary and Tertiary
Mesozoic?	150 million years?	Unknown	Jurassic?
Permo-Carboniferous	300 million years	50 million years?	Permian and Carboniferous
Late Ordovician	450 million years	25 million years?	Ordovician
Varangian or Eocambrian	600 million years	20 million years?	Upper Proterozoic
Sturtian or Infracambrian I	750 million years	50 million years?	Upper Proterozoic
Gnejso or Infracambrian II	900 million years	50 million years?	Upper and Middle Proterozoic
Huronian (probably two or three ice ages)	2,300 million years	200 million years?	Lower Proterozoic

Table 1 (John, 1979)

With the recent discovery of the Ordovician-Saharan ice age, a rather regular interval on the order of 150 million years seems to separate the great periods of continental glaciation with the exception of a Mesozoic ice age. Paleomagnetic evidence suggests that during the Jurassic period, approximately 150 million years ago when a major ice age would have "fit" the cyclic pattern, no major land mass occupied the north magnetic pole. The Gondwana Pole was located somewhere on the present Antarctic continent, and in all probability, the evidence for a major ice age during this time (if it exists) would be buried somewhere under the present ice sheet. Two factors which would oppose the existance of a Jurassic Ice Age are the lack of a major orogeny either before, during, or after this time period (see figure 1), and a high degree of inundation of existing continental land masses.

It is interesting that the relatively periodicity of ice ages was used by several scientists to predict the existance of an Ordovician Ice Age before the actual glacial deposits confirmed it (Fairbridge, 1975). The second line of evidence came from the increased wealth of paleomagnetic data which was used to trace the position of the south pole from its present location in Antarctica, through South Africa during Permo-Carboniferous times, back to its location south of the Sahara during Ordovician times. The third line of evidence must, of course emanate from actual field confirmation. It is important to keep in mind how diagnostic certain sediments are in confirming or not confirming past glacial evidence. Table 2 gives an indication of the relative importance of sediments as glacial indicators.

Indicators of Ancient Glaciation or Cold Climate

(1 = diagnostic; 4 = not diagnostic)

Glacial tillite (1)
The classical basis of inference of ancient glaciation. Diagnostic, especially if underlain by glaciated bedrock surface.

Boulder pavement, streamlined form moulded in till, glacial-drag structure (2)
Supplement glacial tillites. Strongly indicative.

Glacial rythmite with dropstones (1)
Diagnostic.

Dropstones in non-rythmic sediments (2)
Strongly indicative even if dropstones lack glaciated forms.

Ice-contact stratified drift (1)
Diagnostic if arkosic and if clasts with glaciated shapes and striations are present.

Outwash sediment (1)
Arkosic fluvial conglomerate, with clasts having glaciated shapes and striations, and/or sand grains with glacial surface microtextures.

Loess (3)
Not diagnostic, but has supporting value if associated with a tillite.
Glacial-marine sediment (both coastal and deep sea types) (1)
Diagnostic if some coarse clasts possess glaciated shapes or if sand grains have glacial surface microtextures.

Taluses, frost cracks, ice-wedge casts, patterned ground (4)
Not diagnostic in themselves.

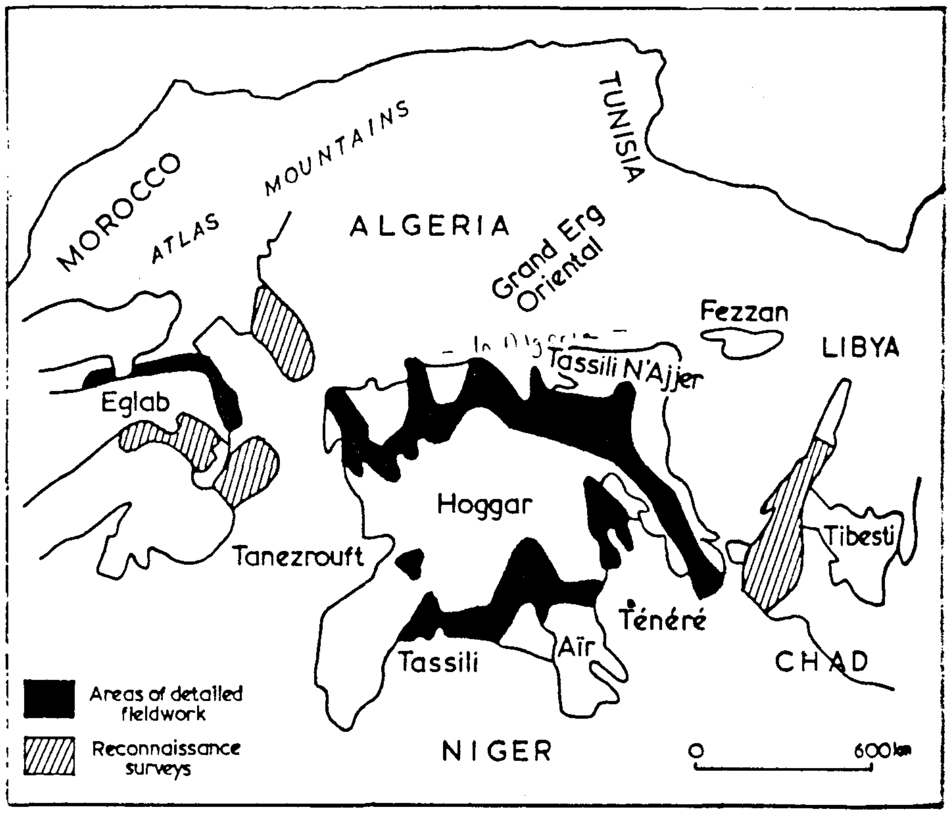
(Table 2; Flint, 1975)

ORDOVICIAN GLACIATION: EVIDENCE AND ANALYSIS

The existance of the Ordovician Ice Age has only been confirmed within the past fifteen years or so. This is not too suprising since most of the evidence comes from the barren subtropical desert where geologic field work is still at the reconnaissance stage. By comparison, the existance of the great Permo-Carboniferous glaciation in South Africa was ascertained as early as 1900 with the correlation of the Dwyka Tillite to that of similar units in India and Australia. To be sure, with the relative accessability of deposits, it is not suprising that even as late as 1960, this was the only firmly established glacial episode known to have affected the African continent, outside of the Quaternary glaciations of the Atlas Mountains in Morocco (Harland and Herod, 1974).

It was during the 1960's that French petroleum geologists began to survey the barren desert world of the Sahara, particularly the area known as the Hoggar Massif in southern Algeria. Other adjacent areas in southeastern Morocco and eastern Lybia were also surveyed (see figure 3). It was in this corner of northwest Africa that the French geologists, particularly S. Beuf, made the initial discoveries of Ordovician glacial features.

The first lines of evidence uncovered were giant boulder beds with characteristic scratch marks and parallel trending grooves, ranging from 50cm to 2m in width. These were exceptionally well preserved under drifting sand dunes in the area east of the Hoggar Massif. Other features similar to modern eskers were also noted. In 1970, an international team of glacial experts was invited by the French geologists to view the evidence. They noted that the



Map of northwest Africa, showing the areas where French petroleum geologists made the main discoveries of Ordovician glacial features in the period 1960-70.

(Figure 3; Fairbridge, 1975)

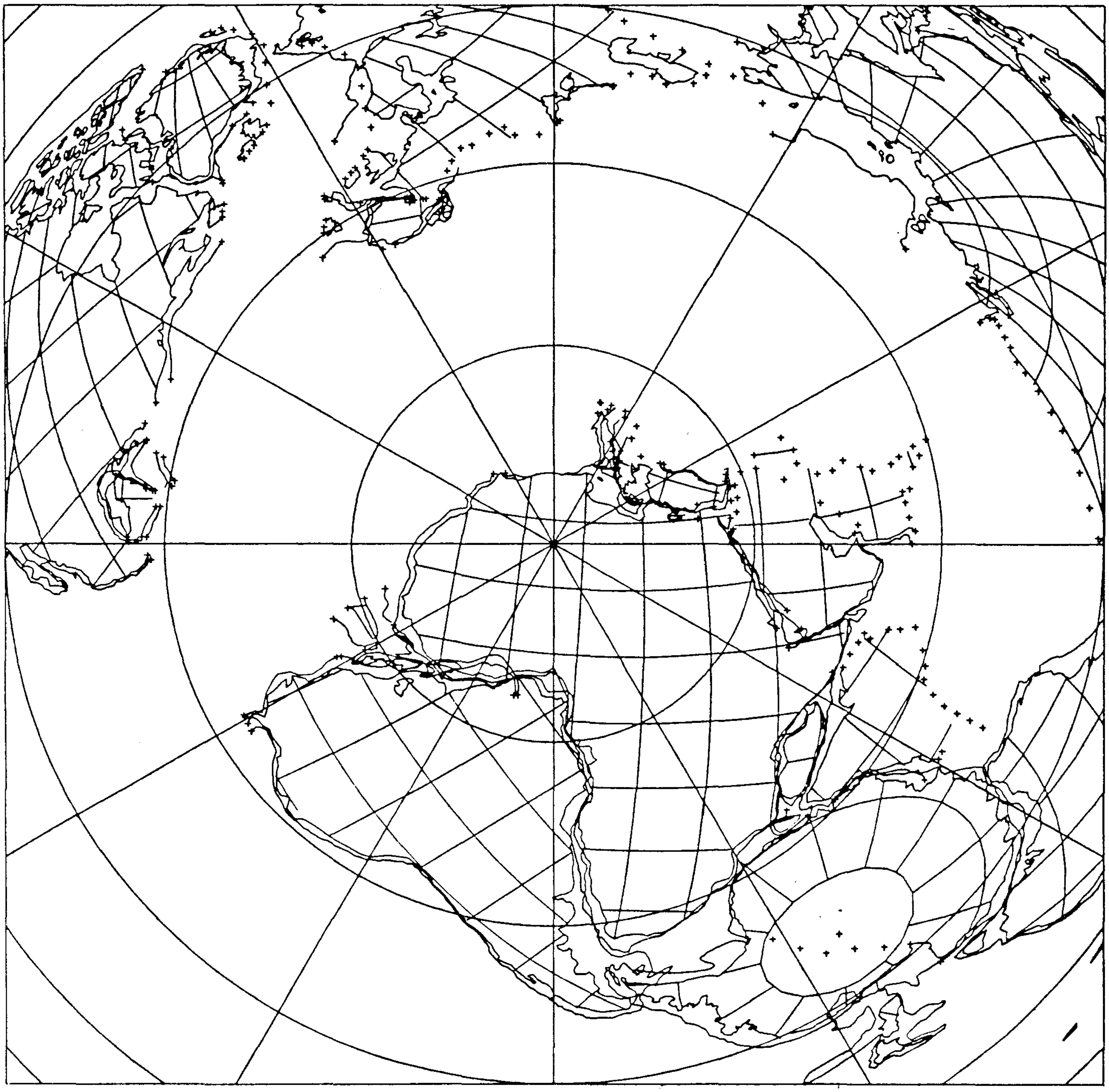
grooves were marked with abundant crescent shaped chatter marks typical of those created by pebbles at the base of modern glaciers. Inside of the grooves, there were very small current ripples (few mm in size) which were oriented obliquely to the ice movement directions. These are thought to have been formed as the ice, advancing on rock, melts into a thin meltwater film as pressure is applied, similar to the blade of an ice skater gliding while applying pressure to the ice surface (Fairbridge, 1975;John, 1979). Abundant roche moutonnees were discovered. Characteristically asymetric and rounded, the smoothed impact sides were found to be well striated.

The grooves were tracked over sizeable distances. To the north, curved and even right angle turns were noted but with the grooves still retaining their parallelism. To the south, closer to the Hoggar Massif, the grooves were very straight, with no evidence of any curvature. Yellow outwash sands were also found; attributed to the deposition of glacial outwash sediments, they were viewed as being analagous to present day outwash sediments found in Iceland.

These characteristic glacial "fingerprints" were set within Upper Ordovician, today viewed as being mainly Caradocian, beds exhibiting well documented fauna assembleges--trilobites, articulate brachiopods, and tubular Skolithos trace fossils. Hence by 1970, the team concluded that in the midst of the world's hottest desert at around 25° N. Latitude, there was unquestionable evidence for the existance of a major episode of continental glaciation during the Ordovician (Fairbridge, 1975, 1970).

Ordovician General History

The Ordovician world was very different from that of the present day. It was a time when continental landmasses were widely dispersed and whose outlines probably appeared vastly different than those of the present day. Paleomagnetic and fossil evidence suggest that the ancient cratons of North America, Europe, and Siberia were situated in tropical or subtropical areas, while part of the supercontinent of Gondwanaland can also be considered to be subtropical. While no landmasses have been placed near the north polar regions, it has been ascertained that a major part of the Gondwana supercontinent was located in the high latitudes above 60° S. latitude (see figure 4).



Relationship of the land masses of the Gondwana supercontinent to the location of the south magnetic pole during the Late Ordovician (approximately 450 million years ago).

(Figure 4; Smith et al, 1981)

It is generally agreed upon that the south pole migrated from Northwest Africa in Cambrian time, across the Sahara region, and into the area between the Sahara and the Congo Basin by the Late Ordovician.

Overall, large areas of the continental margins were submerged by shallow seas during the Ordovician period, with evidence suggesting a number of marine transgressions and regressions. Sea floor spreading is known to have been quite active, as were plate margin collisions responsible for the creation of mountains, and in part, a high degree of volcanic activity. Certain areas, particularly the continental interiors of ancient Siberia and the Australian sector of Gondwanaland, show abundant red-beds and evaporites, leading most to conclude that the climate here was warm and dry. The high latitudes, by comparison, were more than likely dominated by permafrost during the extended period of climatic cooling which culminated in the ice age. In the middle and high latitude seas, the water temperatures fell substantially enough to cause the subsequent reduction in previously abundant graptolite facies of Cambrian waters. Thus by the Mid-Ordovician, approximately 475 million years ago, the climate had cooled enough to iniate the Ordovician Ice Age in the high latitude areas of the Gondwana supercontinent (Fairbridge, 1975).

Stratigraphic Setting

In what is basically a flat desert penplain, the Hoggar Mountains rise majestically out of the southern Algerian desert. An uplift of mainly metamorphic amd igneous rocks, it provides the setting for the discovery of the first documented Ordovician glacial deposits. It is in the Lower Paleozoic sediments which drape around the Massif that four distinctive units were mapped by Beuf. Unit I consists of basement Precambrian gneisses, schists, granites, and rhyolites which have been since eroded into a very flat penplain. Interestingly, the upper few meters of basement were clayified before the unconformably overlain Ordovician sedimentary sequences were deposited. A few centimeters of red hematite form a ferruginous cap to these basement rocks. This cap has been hypothesized to be a paleolaterite, which by present day chemical weathering analogy, would imply conditions indicative of at least a subtropical climate (Allen, 1974, after Beuf, 1971). If we assume this to be the case, then a heavy latitudinal shift over the course of 100 million years of so would have been necessary to bring the craton to a favorable position for the onset of glaciation by the Mid-Ordovician.

The contact between Units I and II is a sharp unconformity of Lower Ordovician sandstones, containing little clay, but exhibiting thin silt structures which outline bedding planes. Cambrian sediments are absent and it is worth noting that no Precambrian pebbles are found in the small layer of poorly developed basal conglomerate which immediately overlies the basement rocks. Large scale trough cross-bedding indicates northerly current directions, and together with faunal relicts of trilobite trails and articulate brachiopods, an overall setting of Lower to Mid-Ordovician marine depositional environments is suggested (Allen, 1974).

Progressing upwards, Unit III is an arenaceous formation disconformably overlying the highly irregular erosional surface which traverses Unit II. In general, there must have been rapid erosion of land surface during Ordovician times due to the fact that there was little land vegetation to counteract the effects of surface water runoff (Fairbridge, 1975). This formation contains many vertical burrows, probably deposited under subtidal shelf conditions, followed by thin horizons of oolitic ironstone and phosphatic nodules. The beds tend to be slumped down steep slopes on top of the disconformable surface. Interestingly, at the top of Unit III, distorted bedding, high-angle thrust faults, and drag structures are locally occurring, providing evidence of shearing pressures applied to these structures (Allen, 1974).

Glacial Deposits

Unit IV lies disconformably on a deep ravined surface which is cut into the underlying bedrock. Well represented on the north flank of the Hoggar Massif, it is this unit which demonstrates highly diagnostic glacial tillites. The deep northerly trending valleys which cut into the erosion surface, show classic U-shaped profiles and are well dissected. These paleovalleys are floored with boulder composed tillite overlying grooved polished surfaces with many of the grooves exhibiting curved but parallel trends. These are highly indicative of irregular motion patterns characteristic of calved icebergs (Allen, 1974).

A typical sequence of Unit IV tillite shows a grooved and glacially eroded surface at the bottom. Overlying the polished pavement is basal tillite, containing striated erratic cobbles and boulders of both igneous and sedimentary origin. Above the tillite deposits are glacio-marine sediments of graded silts and fine sands. Characteristic of a continental margin area, these show rythmic bedding and contain dropstones. Overlying these sediments are waterlain siltstones, sandstones, and conglomerates which have been interpreted as outwash sediments deposited during warmer interglacial periods.

This tillite sequence is repeated at least three times in the area near the Hoggar, and provides good evidence for establishing three seperate advance and retreat situations for the glaciers. Outwash deposits in the two uppermost cycles show large ripple structures associated with conditions of very high water discharge. These are interpreted as strong evidence of catastrophic flooding due in part to the isostacy of the land when compressed under large ice volumes (Fairbridge, 1975).

Other features of glacial significance include well recognizable eskers, composed almost entirely of cross-bedded sandstone. These northerly trending features flank the ravines and can be traced for many kilometers. It is believed that these ridges were formed subglacially by meltwater flowing northerly to a melting ice margin. Evidence of sand volcanoes are found in the Hoggar region, the caps of which are numerous on the desert floor. Erosion of nearby surface layers reveal silica feeder pipes which extend to the desert floor caps. These are postulated as being due to pressure exerted by advancing ice tongues upon waterlogged sandy formations (Allen, 1974). Kettle collapse features are also abundant. Together with the volcanoes, these are indicative of permafrost conditions.

To the east of the Hoggar Massif, the 1970 glacial team discovered several ring structures upwards of a kilometer in diameter. The edges are comprised of Ordovician sandstone which was thrusted abruptly upwards and back over themselves at 45°. Outcrops occurring in several of these structures are composed of a fine-grained basalt surrounded by masses of breccia. Modern Icelandic jokulhlaups, volcanic eruptions under an ice sheet, provide an analogy by which rapid melting and flooding probably occurred.

Critics of the continental glaciation hypothesis for this area have argued that the Hoggar Mountains were uplifted during the Caradocian (Mid to Late Ordovician) and that the tillite sequences were due to alpine rather than continental glaciation. Due to the extremely flat nature of the surrounding penplain, upon which grooves are traceable for over 100 km, and a lack of substantial conglomerate deposits, this alpine explanation is not too likely to have been have been the sole contributor of glacial sediments. Other arguments have been stated that the tillites discovered were actually due to landslides occurring out of the Hoggar Massif. However, this could not have been the case over the extremely vast area and surrounding flat topography (Fairbridge, 1975).

<u>Saudi Arabian Tillites</u>

In the Qasim area of north central Saudi Arabia, rounded and faceted boulders, both sandstone and granitic, occur above an Upper Ordovician-Caradocian shale member of the Tabuk Formation. The boulders occur as clasts in tillite beds that cap the shale scarp and exhibit striations and grooving on their highly polished surfaces. Parallel grooves at the base of the unit trend northeasterly. The granite boulders are coarse with little striation whereas the sandstone boulders tend to be fine-grained and heavily striated. The fresh appearance of the boulders indicate relatively rapid burial, possibly due to catastrophic flooding (McClure,1978).

The tillite deposits are basically non-stratified, poorly sorted, and contain clasts ranging in size from fine-grained quartz particles to the large erratics. The lithologies include sandstone, shale, igneous, and metamorphic rocks. Angular soft claystone fragments ripped from the underlying Ra'an Shale are especially noticeable within the argillaceous matrix. Tillite units are not especially thick, generally around 10m. They are both lenticular and laterally discontinuous in nature. Other curious features include a northeasterly trending paleovalley which shows evidence of glacio-fluvial scouring action as the ice retreated. During the Silurian transgression which followed the deglaciation period, this valley is presumed to have been torrentially filled, as evidenced by the high-angle cross-bedded sandstones. This feature is thought to correlate with the high degree of ravinement found at the base of Unit IV in North Africa (McClure, 1978). Varved rythmites and kettle-collapse features are also found near are also found near the paleovalley, and are suggestive of seasonal meltwater fluctuations and permafrost.

Similarities between these Arabian sediments and the North African glacial deposits, some 4,000km to the west, are evident. The Ordovician sediments below the tillite contain similar fossils to those found in North Africa. Cruziana, Skolithos, and Harlania trace fossils have been found in both sections, implying that the Late Ordovician depositional environments must have been similar. The Arabian section of the craton provided a stable platform for uninterrupted sedimentation to occur from the Late Precambrian. Hence Cambrian deposits are found here although they are lacking in the North African sections. Inferred direction of ice movement, to the northeast, is expected due to the location of the Gondwana pole during the Latest Ordovician.

<u>Paleozoic Glacial Rocks in Ethiopia</u>

During a 1971 mapping expedition through the northern regional provinces of Ethiopia, a large section of previously Mesozoic regarded rocks was reexamined. It was found that a large portion of a basal sandstone unit was found to be of glacial origin. The glacial rocks were of two facies: a) the tillite facies informally named the Endaga Arbi Tillite which grades northwards into b) sandstone facies called the Enticho Sandstone. General stratigraphy of the region consists of low-grade Precambrian metamorphics, which are overlain with a profound unconformity by an essentially flat-lying sequence of marine sedimentary rocks ranging in age from Paleozoic to Lower Cretaceous.

The tillite facies occur below the Adigrat Sandstone Formation, Lower Mesozoic in age. They are unsorted and contain a random distribution of megaclasts of a variety of lithologies; the great size range of components is from fine rock powder to erratic blocks 6 meters across. The tillite, generally 150 to 180 meters thick, is relatively uniform over hundreds of square kilometers. Other features include hummocky forms characteristic of roche moutonnees, striations, grooves, and crescent-shaped chatter marks. The tillite contains lenses of conglomerate up to half a meter thick containing striated pebbles. These lenses show signs of slumping, reflective of the unstable nature of the tillite after deposition (Dow et al, 1971).

The tillite grades upwards into massive shale and siltstone containing few erratic pebbles and cobbles. The subaqueous nature of this upper section is exemplified by beds up to one meter thick of fine pebble conglomerate and less frequent beds of laminated shale and siltstone. Due to the presence of dropstones, these are interpreted as being glacio-marine in origin. The uppermost section of the unit contains no evidence of glacial origin.

Correlation of the Ethiopian glacial rocks had initially presented a problem, since the rocks had previously been thought to be a component of the overlying Mesozoic strata. Once realized to be glacial, the age was put in question; either Late Paleozoic belonging to the Permo-Carboniferous glaciations, or earlier Paleozoic belonging to the Saharan-Ordovician glaciations. Oweing to the unconformable nature of the deposits overlying Precambrian units, they were not thought to be associated with the earlier Eocambrian glaciation which had affected the Congo Basin.

The authors of the work on Ethiopian glacial deposits presented two equally convincing arguments for either Permo-Carboniferous or Ordovician aged rocks. However, due to the additional distance of 2,000 kilometers further away from the Gondwana Pole including a separation by a major sea, made Permo-Carboniferous age questionable (Dow et al, 1971).

The location of the Gondwana pole during the Ordovician seemed more plausible. With the discovery of Ordovician glacial deposits in Saudi Arabia, near the Chad-Sudan border, and extensively in the Sahara, the evidence pointed very convincingly to Ordovician in age (Fairbridge, 1975). This is coupled with the fact that the Gondwana Pole was located in a more centralized location during the Ordovician period.

Glacio-marine Sediments in Sierra Leone

The discovery of Late Ordovician glacio-marine sediments in the Saiona Scarp Group is of major importance in that it provides a southwest boundary for the ice margin. The scarp group covers approximately 50km^2 of northern Sierra Leone and extends into southern Guiniea. It rests unconformably on folded metamorphic and igneous Precambrian rocks. It consists of two formations, the lower being the 40m thick Moria Formation and the upper being the 150m thick Waterfall Formation. The Moria Formation consists mainly of sandstones and basal conglomerate beds with a slight shale occurrence at the top. A shallow marine environment is suggested by the supermaturity of sediment and local occurrence of herring-bone cross-bedding (Reid and Tucker, 1973).

The Waterfall Formation contains the diagnostic glacio-marine sediments. Two distinct facies are recognized, the first being a mudstone with exceptional rythmic bedding of coarse and fine grained laminae. Scattered within this dominant rock type of the formation are numerous angular to subangular clasts which occur randomly and truncate the rythmites. The dropstones are typically 3 to 10 centimeters but do reach upwards of 30cm for larger clasts. Interbedded within the rythmites are lenses of sandstone up to 10 meters in width and 2 meters deep. Constituting the second major facies, these show fining upwards characteristics and some cross stratification.

The interpretation of the Waterfall Formation shows clear evidence of glacio-marine conditions with beautifully preserved rythmites and dropstones. The alternating coarse and fine layers are attributed to seasonal melting conditions from a floating shelf glacier. The dropstone clasts were dropped from icebergs calved from the existing shelf glacier while the rythmites are viewed as slope deposits in the foreground of a glacial delta (akin to muds deposited in front of fluvial deltas). The sandstone lenses, with grading and sole structures, are attributed to turbidity currents in slightly deeper water conditions.

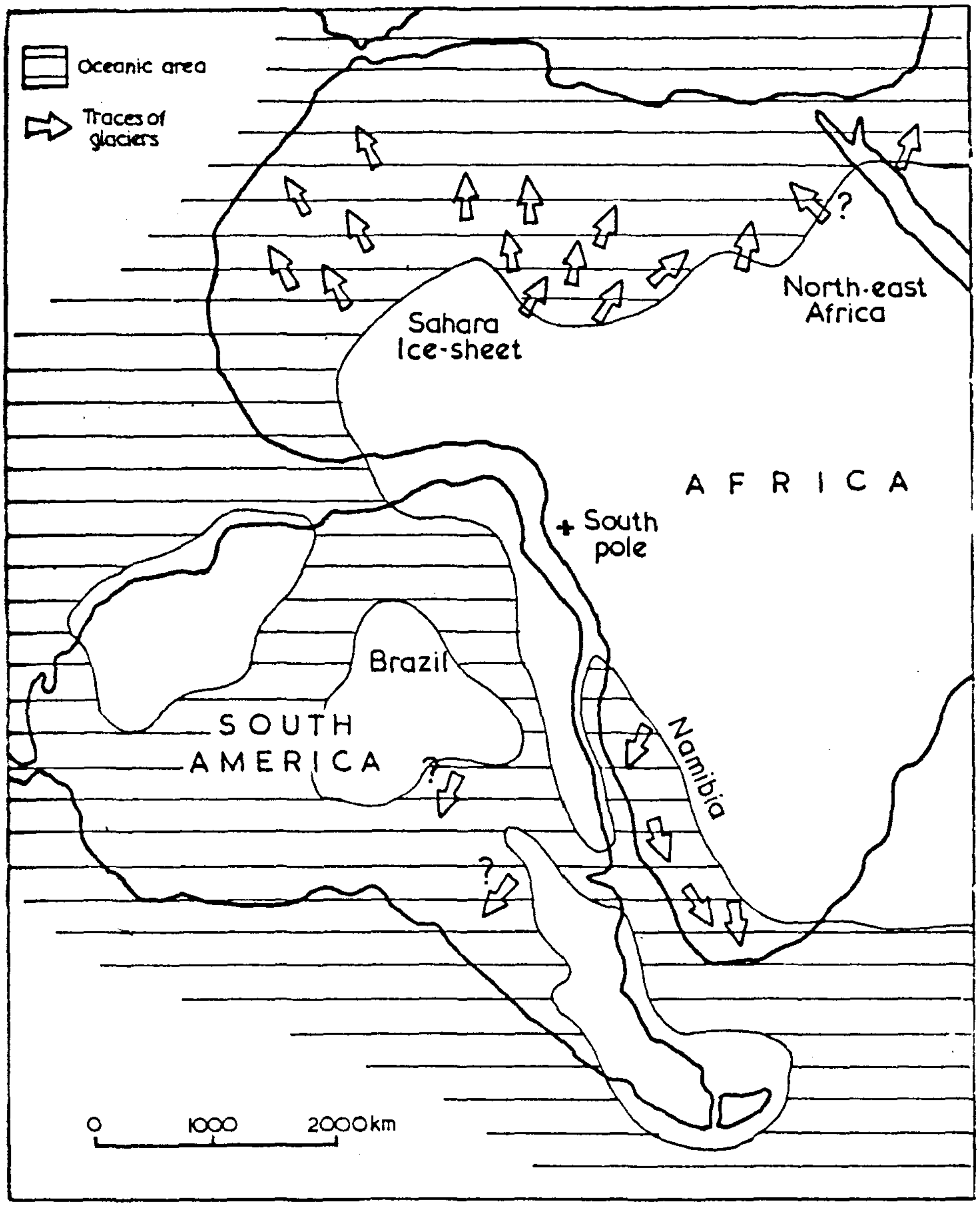
The deposits of the entire Saiona Scarp Group have been correlated as being Late Ordovician, confined mainly to the

Caradocian, and are thought to be evidence for the southwest boundary of the Saharan ice sheet. Apparantly, this sector of the ice sheet was the extent of the floating ice shelf and would be analagous to present day sonditions in the area of West Antarctica (Reid and Tucker, 1973).

CONCLUSIONS

It is to be expected that as one proceeds farther back into geologic time, ice age evidence would presumably become more and more fragmental. This is why the Ordovician evidence, exceptionally well preserved, is so convincing. Arguments for this high level of preservation have been postulated along the lines of a sedimentary basin which developed in the area following the glaciation. This is in part due to a major sea level rise thought to have taken place in the Early Silurian (Wright and Mosely,1975).

Most experts generally place the Ordovician glaciation in the Mid to Late Ordovician, confining the limits to be mainly Caradocian. The extent of glacial deposits correlating as Ordovician have provided some interesting estimates for the extent of ice coverage. If the known glaciated areas represent a continuous ice mass, then the approximate area involved would be over 20 million square kilometers. By comparison, the present day Antarctic ice sheet occupies some 14 million square kilometers, twice the size of the contiguous United States. Figure 5 depicts the overall coverage of Ordovician glacial evidence. With the vast area affected, it is more than likely that multiple ice centers were responsible, such as in the Pleistocene glaciations of North America (Fairbridge, 1975). Even with such multiple ice centers, it is also though that the ice age was very similar to



Areas where traces of Ordovician glaciation have been found. Note that the land areas were somewhat different from those of today. The location of the south magnetic pole is much farther south in Fairbridges placement than in Smith's analysis (see figure 4 for comparison). The glacial evidence in South Africa is dated Ashgillian (Latest Ordovician) while North African deposits are inferred as Caradocian (Mid to Late Ordovician).

(Figure 5; Fairbridge, 1975)

conditions which exist today in Antarctica; specifically the existence of both widespread continental ice sheets, such as in East Antarctica, and large floating ice shelves characteristic of West Antarctica. In Algeria, as one progresses northwards from the Hoggar region, the Ordovician aged rocks plunge gently downwards into a broad basin. The sandstone units thicken, indicative of a more open seaway which evidence suggests was filled with floating ice. Specifically the curving of parallel glacial grooves is due to floating icebergs subject to winds and/or currents changing quickly (Fairbridge, 1975). Iceberg grounding also creates irregular scouring by the deep projection of the ice-berg below the surface. The central Sahara shows evidence of these situations to the north.

With respect to the vast area involved and the likelyhood of multiple ice centers, it is feasible that the ice sheets merged at one time or another creating a vast ice desert. Towards the centers, where warm moist air would have difficulty reaching, areas of thin snow and permafrost seem quite likely to have dominated (Fairbridge, 1975; Allen, 1974; Wright and Mosely, 1975). This situation takes on additional significance if one considers that within outcrops located in South Africa, particularly in the thick lagoonal and littoral sequences of Cape Town, South Africa, well documented glacially striated pavements and glacio-marine sediments occur. These tillites, due to a reevaluation of faunal evidence, particularly marine brachiopods, are now correlated as Late Ashgillian (Latest Ordovician). Although the Saharan tillites are generally Caradocian and the South African deposits probably can not be regarded as belonging to the same ice sheet system, they are possibly an end member of the same general ice age. This would further the notion of an extensive ice desert located in the central region of the craton, especially if one considers that the distance between Cape Town and Morocco is 6,000 km.

The North African evidence has implied a lifespan of the Ordovician Ice Age of around 25 million years, roughly half that of the Permo-Carboniferous glaciations. At least three advance and retreat cycles are documented and evidence suggests that the glaciers along the northwest margin were probably warm-based. The deglaciation period was followed by a rapid migration of the Gondwana pole to the south. It is thought this became a relatively warm period in the earth's history. Certainly, no more glaciations are known to have affected North Africa except for the Quaternary alpine glaciers of the Atlas Mountains in Morocco. This relatively warm period ended some 150 million years later with the onset of the next great ice age.

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